

# **THE STRUCTURAL CHANGES OF TROPICAL CYCLONES UPON INTERACTION WITH VERTICAL WIND SHEAR**

## **FINAL REPORT**

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### **1. Overview of the Problem:**

It is well known that a mature tropical cyclone has the potential to cause serious damage and loss of life. Whereas some storms have relatively little impact, even highly destructive storms often exhibit extremely small-scale variations in their damage patterns. As global population and wealth has become increasingly concentrated along vulnerable coastlines, interest has grown in discovering the processes that govern the intensities and core structures of tropical cyclones and how to predict these quantities.

There have been many studies of the mean, quasi-steady structures of mature tropical cyclones (e.g., the review by Willoughby, 1995). Some features of the storm circulation are nearly axisymmetric, such as the pressure and temperature anomaly patterns. The tangential wind field is predominantly axisymmetric but usually exhibits a significant wave number one asymmetry as well. In contrast, the distributions of rainfall, convection and radial winds can vary dramatically from nearly symmetric (usually observed only in very intense storms) to highly asymmetric. The degree of asymmetry in the tropical cyclone core is neither well documented nor well understood. This topic is important since understanding the distribution of winds and rain in tropical cyclones is vital to both forecasting and understanding these dangerous storms.

Vertical wind shear is the primary mechanism that weakens mature tropical cyclones to intensities that are considerably below the theoretical maximum (Emanuel 1987; Holland 1997).

Whereas physical mechanisms causing the weakening have been studied using numerical weather prediction models, their applicability to the real atmosphere remains unknown, mainly because few high resolution datasets that are required to study structural changes in hurricanes exist. Previous studies (e.g., Jones 1995; DeMaria 1996; Bender 1997; Peng et al. 1999; Frank and Ritchie 1999, 2001) have used numerical simulations of idealized tropical cyclones to study the effects of vertical wind shear on the structure and intensity of tropical cyclones. DeMaria (1996) hypothesized that the shear caused the storms to tilt downshear, with the result that the upper-level warm anomaly would advect over the downshear portion of the eyewall, stabilize that region, and reduce convection there. Although this would create asymmetries in the eyewall structure that might have a negative effect on storm intensity, it seems contrary to satellite imagery that indicates a suppression of core convection on the upshear side.

Jones (1995) performed simulations of tropical-cyclone-like vortices in a dry model and found that the shear caused the vortices to tilt downshear and to develop a wave number one asymmetry in the vertical motion pattern. In her dry simulations, the vortices went through a two-stage process that resulted in maximum upward motion downshear-right of the center, with maximum forced subsidence occurring to the upshear-left side.

Bender (1997) performed simulations of a tropical cyclone in vertical shear using the Geophysical Fluid Dynamics Laboratory model. He found that the vertical shear produced asymmetries in the eyewall structure, and he attributed these asymmetries to effects on the vorticity field caused by the symmetric flow relative to the moving vortex. The action of the winds on the vorticity field caused forced uplifting at lower levels, which tended to organize the convection, and thus the rainfall, in the eyewall into preferred patterns. In general, the convection was favored to the left of the shear, although the maximum accumulated rain tended to occur on the upshear side of the storm.

Frank and Ritchie (1999, 2001) performed a series of numerical simulations of idealized tropical cyclones using MM5 (Penn State/NCAR Mesoscale Model, Version 5), which is a nonhydrostatic, three-dimensional model that includes both parameterized and explicitly resolved moist processes. They compared dry and moist simulations with similar initial conditions to examine the behavior of a sheared vortex when latent heat release was allowed to occur. Their simulations were performed on an f-plane to simplify the relationship between the imposed

domain-average shear and the shear affecting the storm inner core. They examined values of shear ranging from a relatively weak 3 m/s through 15 m/s. They found that the latent heat release in the eyewall region resulted in stronger vertical coupling of the storm than occurs in dry simulations, and thus a greatly reduced tilt of the vortex. As the eyewall began to saturate, and the model's explicit moisture scheme became active, the convection tended to shift from the downshear-right quadrant predicted by the dry models to the downshear-left quadrant (Frank and Ritchie 1999). Complex asymmetries developed as a result of the interaction between the tropical cyclone vortex and the imposed vertical wind shear. Nonetheless, their storms tended to produce a persistent wave-number-one asymmetry in the distribution of convection and rainfall, with both quantities being maximized on the left side of the shear vector.

These simulations suggest that even relatively weak shears ( $5 \text{ m s}^{-1}$ ) may cause major asymmetries in storm structure and reductions in tropical cyclone intensity. For weak to moderate shear, the weakening of the vortex lags the development of the core asymmetries, which may be one reason why the relationship between vertical wind shear and storm intensity is not straight forward (Frank and Ritchie 2001). In addition, tropical cyclones in substantial shear, although rapidly weakening, may develop and maintain a low- to mid-level vorticity structure and enhanced low-level warm temperature anomaly long after tropical characteristics can no longer be detected in infrared satellite imagery (Ritchie and Elsberry 2001). These tropical cyclones exhibit extremely asymmetric structures with convection and precipitation in a concentrated triangular region to the front-left side of track. These persistent convective asymmetries appear to be caused by the response of the tropical cyclone vortex to the shear, which is acting to unbalance the flow, and due to enhanced frictional convergence due to the motion of the vortex.

In summary, the simulated interaction of a tropical cyclone with vertical wind shear results in the development of persistent and predictable asymmetric convection and precipitation in the eyewall structure of tropical cyclones that may be related to changes in storm intensity. In fact, several of the above studies indicate that both the structure of the storm and any change in storm intensity may be predictable from knowledge of the environment flow fields into which the storm is moving. However, a lack of high-resolution data sets of the tropical cyclone core

structure throughout the troposphere and lower stratosphere have limited our ability to test these hypotheses and separate cause and effect.

The Fourth Convection and Moisture Experiment (CAMEX-4) provided a unique opportunity to observe the distributions and document the roles of important atmospheric factors that impact the development of the core asymmetries and core structural changes of tropical cyclones embedded in vertical wind shear. The state-of-the-art instruments flown on the NASA DC-8 and ER-2, in addition to those on the NOAA aircraft, provided a unique set of observations that documented the core structure throughout the depth of the tropical cyclone. These data have been used to conduct a combined observational and modeling study using a state-of-the-art, high-resolution mesoscale model to examine the role of the environmental vertical wind shear in producing tropical cyclone core asymmetries, and the effects on the structure and intensity of tropical cyclones.

## **2. Scientific Objectives.**

The scientific objectives of this study were to obtain *in situ* measurements that would allow documentation of the physical mechanisms that influence the development of the asymmetric convection and its effect on the core structure of the tropical cyclone. These data would allow the investigators to:

- 1) verify the development of a vortex tilt associated with the development of convective asymmetries.
- 2) provide documentation of changes in the core structure that are directly related to the interaction with vertical wind shear. In addition, other environmental factors relating to intensity change including the underlying sea-surface temperatures, would be documented and studied.
- 3) partition the effects of different environmental influences on the tropical cyclone structure to better understand how different environmental factors affect tropical cyclone structure and intensity.
- 4) gain a better understanding of the processes occurring in the core of the tropical cyclone due to the interaction with the environmental shear and establish cause and effect between different processes occurring in the tropical cyclone core during interaction with vertical wind shear, and the intensity change that occurs.

5) should the opportunity arise then an additional objective was to use the CAMEX-4 observations to identify the physical mechanisms associated with the changes in the warm core structure of the vortex as the tropical cyclone moves poleward into increasing upper-level wind shear associated with the midlatitude circulations.

These objectives were to be achieved by making high-resolution numerical simulations in conjunction with the suite of observations taken during the CAMEX-4 field program. Thus the physical mechanisms that result in tropical cyclone filling due to interaction with vertical wind shear could be examined in a realistic context with the *in situ* observations for validation, but with various environmental switches turned on or off. This would allow a partitioning of the various possible environmental effects on the tropical cyclone structure and intensity. In addition, validation of the numerical model would be invaluable for assessing on a case by case basis whether the prediction of the interaction between the environment and tropical cyclone is useful for forecast guidance. This work is still ongoing.

### **3. Research Results**

#### **3.1 Observational analysis**

The research has been conducted in three parts. The observational component of the research utilized the suite of instrumentation available on the NASA ER-2 and DC-8 aircraft along with NOAA aircraft, ground-based measurements (e.g., rawinsonde observations, ground-based Doppler radar), and remote-sensing instruments of opportunity (e.g., TRMM). At this stage two storms have been examined: Tropical Storm Chantal (Heymsfield et al. 2003) and Hurricane Erin (Halverson et al. 2003). Of particular importance has been examination of the tropical cyclone structure under strong shear (Chantal) and weak shear (Erin). Of particular note was the highly sheared structure of Tropical Storm Chantal, which struggled to maintain intensity under a very strong ( $8 - 15 \text{ m s}^{-1}$ ) southwesterly shear through much of its life. The storm had a poorly defined vortex that only extended up to 5 – 6 km in altitude, and an adjacent intense convective region that comprised a mesoscale convective system (MCS). The entire low-level circulation center was in the clear air on the western side of the storm, about 80 km to the west-southwest of the MCS. A broad warm subsident region was located over the low-level vortex and probably was at least partially responsible for the vortex being in clear air

(Heymsfield et al. 2003). This basic structure has been predicted by idealized modeling studies of vortices in vertical wind shear (e.g., Frank and Ritchie 2001; Ritchie and Elsberry 2001).

Hurricane Erin was estimated to be in about  $4\text{--}5\text{ m s}^{-1}$  of southerly vertical wind shear during the observation times. All the convective activity was confined to the forward quadrants on the left side of the wind shear vector as predicted by idealized studies (Frank and Ritchie 2001). Interestingly, Erin also exhibited pronounced asymmetries in its core structure even though the prevailing shear was relatively weak. The observations paint a coherent picture consistent with theoretical and modeling studies (e.g., Jones 1995; Frank and Ritchie 2001). However, although the modeling studies do predict some weakening of a hurricane under relatively weak shear, Erin was weakening considerably at the time, and this is attributed to her concurrent passage over colder sea surface temperatures (Halverson et al. 2003) rather than due to the vertical wind shear. Details of these studies will be reported under separate grants (PIs J. Halverson and G. Heymsfield).

### 3.2 Data ingestion and analysis

Observations collected during the CAMEX-4 field campaign were used to enhance first-guess analyses from the NCEP final analyses, which are  $1^\circ$  global analyses based on the AVN run, but with a later input data cutoff. The case described here was that of Tropical Storm Chantal and the modeling system used was the PSU/NCAR mesoscale model (MM5). Three grids were

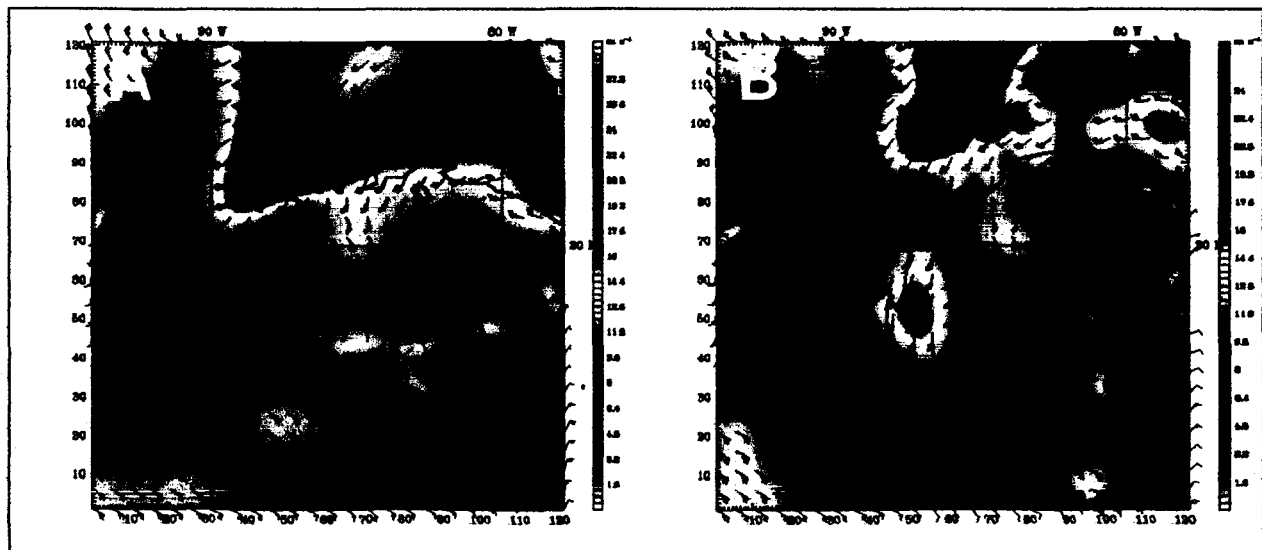
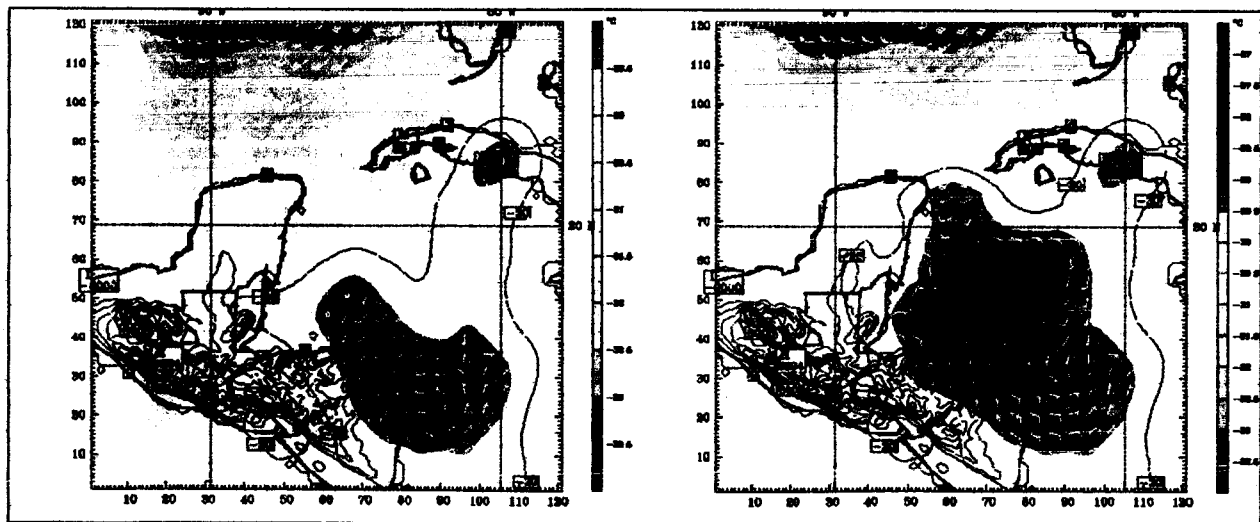


Figure 1: Domain 2 300 mb winds (shading is wind speed; one full barb =  $5\text{ m s}^{-1}$ ): a) NCEP final analysis; b) NCEP final analysis with satellite-derived wind and dropwindsonde observations.

employed: a coarse mesh of 121 x 121 grid points with a resolution of 45 km. A middle mesh of 121 x 121 grid points with a resolution of 15 km, and the finest mesh of 241 x 241 grid points with a resolution of 5 km. Two basic data sets have been employed to date: satellite wind observations made available from the Space Science and Engineering Center at University of Wisconsin Madison, and 27 dropwindsondes from the NASA DC-8 (6) and NOAA P3 (21) aircraft adjusted to account for the approximately 7 hours it took to complete the mission. We plan to also include flight-level data and some other more unique data as well as environmental temperatures from AMSU in the near future (Ritchie et al. 2003).

Both the satellite wind data and dropsonde data had a significant impact on the first guess fields. The satellite winds had the most impact above about 300 mb and below 700 mb, and were important for defining large-scale structures such as an upper-level trough to the north of Chantal (e.g., Fig. 1) as well as the strong low-level easterly winds that extended to the north of Chantal's circulation center. The dropwindsondes had impact throughout the atmosphere and were important for defining mesoscale structure within the storm as well as some of the near environment (e.g., Fig. 2).

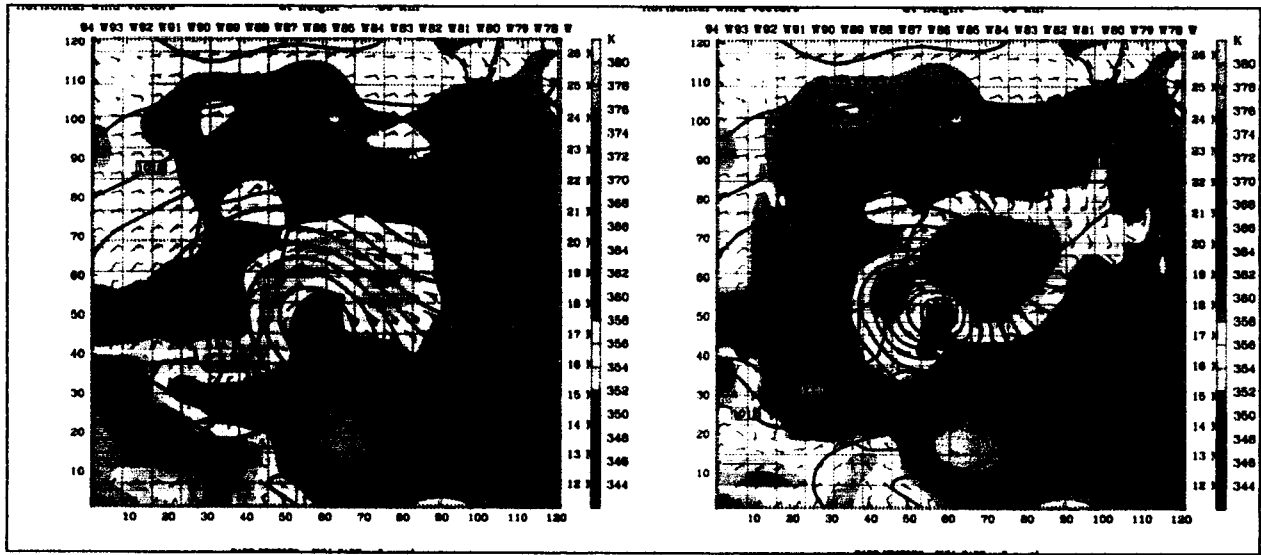
With the addition of the dropwindsonde data, the surface pressure of Chantal dropped from 1008 mb in the first-guess fields to 1004 mb (Fig. 3). Surface equivalent potential temperature ( $\theta_e$ ) values were dramatically altered, with the cooling to the northeast of Chantal's center due to the intense precipitation much more evident in the reanalysis fields (Fig. 3b). The



**Figure 2: Domain 2 300 mb temperature (shading °C) with wind barbs superposed: a) NCEP final analysis; b) NCEP final analysis with satellite-derived wind and aircraft dropwindsonde observations. (full barb = 5 m s<sup>-1</sup>).**

warm  $\theta_e$ 's to the south-southeast of Chantal's center remain unchanged and were probably the source for the intense convective burst.

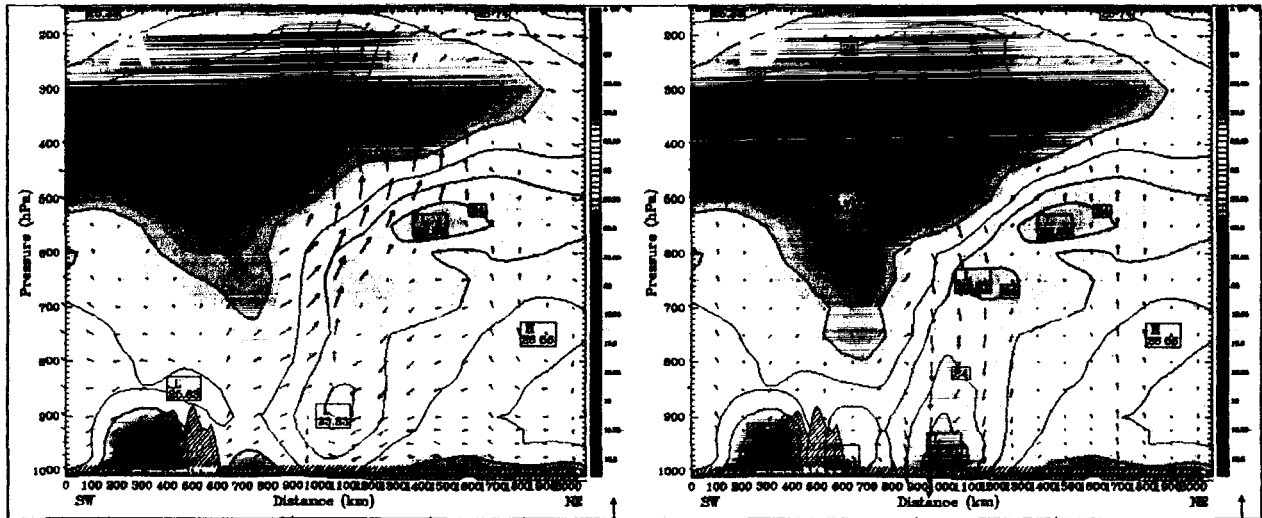
Most importantly, the dropwindsondes had significant impact in defining the tilted warm-core structure of Chantal, as well as the significant cooling associated with the strong convection downshear of Chantal's center (Fig. 4). Compared with the first-guess fields (Fig. 4a), the warm core is much better defined, with a downshear displacement of approximately 200 km from the 700 mb warm core to the maximum at 300 mb (Fig. 4b). The downshear cooling below 800 mb



**Figure 3: Domain 2 surface equivalent potential temperature (colour shading  $^{\circ}\text{C}$ ), sea-level pressure (1 mb contours), and wind barbs (full barb =  $5 \text{ m s}^{-1}$ ) for: a) NCEP final analysis; b) NCEP final analysis with satellite-derived wind and aircraft dropwindsonde observations.**

associated with the strong convection is also well represented (Fig. 4b) compared with the first-guess fields (Fig. 4a). An additional difference between the two analyses is shown in the in-plane circulation vectors. Although strong positive mid-to upper tropospheric vertical motion is indicated in the NCEP final analysis in the location where the MCS is located, there are no low-level downdrafts associated with precipitation (Fig. 4a). However, in the re-analysis (Fig. 4b) mid- to low-level downdrafts are indicated associated with the rain-cooled region. Further analysis reveals complicated mesoscale vertical motion structure. However, in general, the maximum positive vertical motions in the upper atmosphere are collocated with the MCS and are in a location coincident with the low-level inflow and convergence diagnosed in QuikSCAT data





**Figure 4: Domain 2 temperature anomaly (defined as the full temperature field minus the standard profile; shading °C) and in-plane circulation vectors through Chantal's center along the shear vector: a) NCEP final analysis; b) NCEP final analysis with satellite-derived wind and aircraft dropwindsonde observations.**

(Heymsfield et al. 2003). The mid- to low-level downdrafts are coincident with the evaporative cooling from the intense precipitation (e.g., Fig. 4b).

To conclude, we believe that, in general, the structure revealed in the reanalysis data after ingestion of both satellite-derived wind observations, and the aircraft dropwindsonde data is in agreement with that analysed in Heymsfield et al. (2003) using just the observations (Ritchie et al. 2003). These analyses will be used to conduct numerical simulations that examine the effect of various environmental factors on the structure and intensity trends of TS Chantal.

### 3.3 Simulations

The reanalysis fields described briefly above are being used to initialize computer simulations using MM5. Two sets of simulations are being currently being conducted. The first are full physics, full data simulations, and are designed to investigate how Chantal's structure is related to the actual environmental conditions in which she developed. The second are a series of idealizations whereby environmental conditions are changed and the subsequent effect on Chantal's structure is analyzed. Changes in the environment include changing the sea surface temperature to be warmer and colder than the actual temperature. A second change is to remove the land, which Chantal encountered only shortly after the aircraft flights. Chantal was intensifying as she made landfall and we would like to understand how her structure and

intensity would have changed had she not made landfall at that time. These simulations are underway and a continuing part of this study.

### **3.4 Other Hurricanes**

CAMEX-4 provided unique data sets into several hurricanes. Two additional hurricanes we would like to study in particular are Hurricanes Erin (Halverson et al. 2003), and Humberto, which had the unique distinction of consecutive flights allowing a detailed study into the way a hurricane's structure evolves. The reanalysis of Erin is currently underway, and an important part of the study will be to try and understand the importance of the environmental vertical wind shear compared with the decreasing sea surface temperatures on Erin's evolution (Halverson et al. 2003).

## **4. Summary**

A combined observational and numerical simulation study of the interaction between a tropical cyclone and environmental vertical wind shear has been conducted. The observational component is based on the CAMEX-4 field program, which provided a unique opportunity to gather observations of the structure of a tropical cyclone before, during, and after interaction with vertical wind shear. The documentation of structural responses in the tropical cyclone during interaction with vertical wind shear has provided the ability to test hypotheses based on idealized numerical simulations regarding the relationships among vertical wind shear, the development of core asymmetries in the tropical cyclone, and the resultant weakening of the tropical cyclone. This study is ongoing. However, clear progress has already been made regarding understanding the structure of a hurricane under weak and strong shear, and using this understanding to validate the theoretical and modeling studies of hurricanes in shear that have already been conducted.

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